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A new approach to assessing the risk to woodland from pest and diseases

Susan Davies^{1*}, Genevieve Patenaude¹ and Pat Snowden²

¹School of Geosciences, University of Edinburgh, Edinburgh EH8 9XP, Scotland

²Economics and Climate Change, Forestry Commission, Edinburgh EH12 7AT, Scotland

*Corresponding author. Tel: +44(0)796 802 8445; E-mail: susan.davies@ed.ac.uk

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Pests and diseases pose a growing threat to woodlands from both endemic sources, and increasingly, from interregional transmission. Strong comparative analyses of this threat are needed in order to develop preventative measures. Such analyses should include estimates of the potential worst-case loss from all relevant pest and disease (P&D) threats to key tree species. Existing approaches tend to focus on individual assessments of the risk from a single pest or disease, or assessments of overall trends. Effective risk management requires more comprehensive quantified assessments of the overall threat to woodland that includes comparisons of the threat to individual tree species and identification of the potentially most damaging P&Ds. Such assessments support important policy and management decisions including species selection; preventative action; and the size of buffers against losses from forest carbon projects. Here we present a new approach that supports a systematic, risk-based assessment of the future threat to a given woodland from all known individual P&Ds, and to constituent individual tree species, based on a risk management approach taken from the finance sector, but hitherto not applied in an ecological context. Unknown or unidentified pests and diseases can systematically be added in future as identified. We demonstrate the method through a case study evaluating the threat to projects certified under the UK's Woodland Carbon Code. The approach can be adapted to any woodland resource worldwide. Its novelty lies in the simplification of complex threats, from numerous pests and diseases, to measures that can be used by a range of forest stakeholders.

Introduction

Pest and diseases (P&D) represent a major threat to the world's forests (Flower and Gonzalez-Meler, 2015; Wingfield *et al.*, 2015) yet there is a paucity of information on statistical trends on the impact and rate of forest loss caused by P&D (Petrokofsky *et al.*, 2013). Furthermore, the threat is rising: increasing connectivity between markets through growth in international trade, increases the volume of shipping and air transport that can act as vectors for the transmission of P&D between countries, and is leading to increasing introductions of exotic P&D (Lovett *et al.*, 2006; Wingfield *et al.*, 2015). P&D can also be transmitted via infected saplings or other genetic resources (Brasier, 2008; Garnas *et al.*, 2012).

Ecologists, foresters, forest owners, asset managers, policy-makers and investors need to assess and quantify the potential risks to woodlands, including P&D risk, to improve operational management of risk and to factor risk into business, investment and policy decisions (Guy, 2006; Forestry Commission, 2011; Defra *et al.*, 2014a; FIM, 2015). Risk management decisions are traditionally based on worst-case assessments of potential losses rather

than forecasts of expected losses: for example, quantifying the level of loss that will not be exceeded to a 99 per cent level of confidence, as opposed to quantifying the average expected loss (Hopkin, 2014). Such comparable assessments of the threat to individual tree species could contribute to decisions on the risk vs return of planting different species for carbon and timber purposes. Comparisons of the threat from individual P&D could help prioritize research and target resources efficiently at preventative measures. These assessments could also help forest carbon standards, such as the Verified Carbon Standard and the UK's Woodland Carbon Code (WCC), define procedures for determining how much sequestered carbon should be set aside against future losses (Verified Carbon Standard, 2012; Forestry Commission, 2014). Current assessments are inadequate to provide analyses at the woodland, tree species and P&D level, to support such practices as explained below.

Limitations of existing information

In terms of providing the context to this threat, significant qualitative information on P&D exists at national and regional scales, but

little comprehensive quantitative information is available at a global scale that does not focus on individual P&D (FAO, 2009; van Lierop *et al.*, 2015). The 2010 Global Forest Resources Assessment by the Food and Agricultural Organization of the United Nations estimated that in 2005, 1.6 per cent of the world's forests were affected by insects and 0.2 per cent were affected by diseases (FAO, 2010). However, in the most recent assessment (FAO, 2014), countries were asked to report on the most significant outbreaks, but only 75 countries out of 155 were able to report on the area of forest affected by P&D or severe weather (van Lierop *et al.*, 2015). In these countries, P&D and severe weather damaged 141.6 million hectares of forest, or 5 per cent of the total forest area (van Lierop *et al.*, 2015). Of this, 98.0 million hectares of damage was caused by P&D (van Lierop *et al.*, 2015).

A recent analysis found that between 1950 and 2000, living organisms accounted for 16 per cent of the total wood damaged by natural disturbances in Europe, and 8 per cent of this was attributed to bark beetles alone (Schelhaas *et al.*, 2003). Whilst this was the first comprehensive quantitative assessment of the overall historic rate of loss caused by natural disturbances (including P&D) in Europe, it does not provide breakdowns of losses from individual P&D species, or the impact on individual tree species.

Existing records of P&D losses in Britain are sparse. From 1987 to 2006, the Forestry Commission monitored changes in forest condition through surveys, which included damage from insect and fungi (Forestry Commission, 1987–2006). The information provided related to the current state of the crown condition from cumulative attack and did not provide information on mortality. The 2010 UK submission to the FAO's Global Forest Resources Assessment (FAO, 2010) estimated impact using a threshold of 'cause mortality or such severe dieback that the forest ecosystem changes'. Using this criterion around 1000 hectares per year was estimated to be newly affected by disturbance from insects and less for other diseases, equating to significantly less than 1 per cent of the forest area lost per year. However, the Forestry Commission's most recent submission for the UK did not quantify losses at all. It provided a list of recent outbreaks and insects and diseases affecting UK trees but stated that 'estimates of areas affected are not directly available' (FAO, 2014).

The UK Plant Health Risk Register (Defra, 2014b), launched in January 2014 on the recommendation of the independent Task Force on Tree Health and Plant Biosecurity (Defra, 2013), provides a register of key threats to UK crops, trees, gardens and countryside. The pests listed are primarily regulated pests listed in the EU Plant Health Directive (European Council, 2000) and threats identified by the European and Mediterranean Plant Protection Organization (Defra, 2014b), or for which Pest Risk Assessments are available. It focuses on P&D threats not yet present in the UK or not yet at their full range. Existing well-established P&D such as Dutch elm disease (*Ophiostoma novo-ulmi*) are not included. Information listed for each P&D on the register includes a score from 1 (low) to 5 (high) for each of the following factors: the likelihood of arrival and establishment; rate of spread; and impact broken down into economic, environmental and social elements. However, no quantification is provided relating to these scores that could be used for a quantified risk assessment. For example, it is not possible to determine from the annual likelihood of arrival score, what the

annual per cent likelihood or expected year of arrival is; how fast each of the scores for the rates of spread relate to; or what each of the impact scores represent. In addition, it does not provide summary scores or quantifications of the threat to individual tree species from all P&D that might impact it. Whilst the Register is a significant and important source of information about relative threat, it does not contain all the information required as a basis for a systematic and quantified risk assessment.

A large volume of academic research have been dedicated to the biology, management and control of individual P&D, the majority of which do not attempt to quantify the threat that they pose (Inward *et al.*, 2012; Mitchell *et al.*, 2014). Many quantified assessments do exist for individual P&D (Evans *et al.*, 2008; Taylor and MacLean, 2008; Harwood *et al.*, 2009; Brasier and Webber, 2010; Chadfield and Pautasso, 2012; Stadelmann *et al.*, 2013; Straw *et al.*, 2013; Pukkala *et al.*, 2014; Green *et al.*, 2015) but each study uses different methodologies and timeframes and so cannot be aggregated to tree species or woodland level analyses. A range of techniques can be used to assess losses at the woodland resource level, but do not provide breakdowns of the risks to individual tree species or identify all of the constituent individual P&D threats. These include techniques assessing crown condition (Blum *et al.*, 2015; Morin *et al.*, 2015) linking forest scenario models to climate and bark beetle outbreaks (Seidl *et al.*, 2009); frameworks for modelling P&D impacts using tree ecophysiology (Dietze and Matthes, 2014); and models linking net primary production, physiology and pests (Pinkard *et al.*, 2011).

It seems logical that risk assessments for P&D should be based on future threats rather than historical losses. Any risk assessment based only on historical trends will fail to take account of future threats. In Britain, for instance, such an approach would have been blind to the arrival of Dutch elm disease (*Ophiostoma novo-ulmi*) in the 1970s which is estimated to have killed 30 million trees, including over half of the local population in many areas of Southern Britain (Potter *et al.*, 2011), or more recently ash dieback (*Hymenoscyphus pseudoalbidus/Chalara fraxinea*) first reported in 2012 and detected in 639 locations across the UK by March 2014 (Heuch, 2014). Historical trends would also underestimate the risk from those P&D that have not yet reached their full ranges. Here, the fungus, *Phytophthora ramorum*, provides a good example from the UK. The fungus has severely damaged larch (*Larix* spp.) and by 2010, 1900 hectares were estimated to be showing symptoms representing ~0.5 million trees (Brasier and Webber, 2010). Likewise, the threat from P&D for which historical data has not been gathered for long enough to capture cyclical outbreaks or maximum possible losses would be underestimated.

A key source of information on current threats is the network of Regional Plant Protection Organizations (RPPOs), established under the International Plant Protection Convention and spanning the continents. These include for example, the European and Mediterranean, Asia and Pacific and North American Plant Protection Organizations (IPPC, 2015). The regional organizations coordinate the National Plant Protection Organizations within their region and provide standardized Pest Risk Assessments of regionally relevant P&D threats. These assessments contain a wealth of information on the ecology of P&Ds, such as life cycle, dispersal ability, previous outbreak history, characteristics, pathways of establishment, susceptibility of hosts and

treatment. However, they rarely provide quantification of factors such as the likelihood of mortality or rate of dispersal, which are needed for quantified risk assessments. The PRATIQUE project, funded by the European Commission's Seventh Framework Programme for Research and Technological Development, is seeking to address such known limitations in Pest Risk Assessments in future ([The Food and Environment Research Agency, 2015](#)).

Concept behind the P&D methodology

To address these gaps, we present a novel methodology that derives a single measure of the threat to woodland resources, and to its constituent tree species, from the consolidation of standardized evaluations of individual P&Ds threats. Standardization ensures that P&Ds are assessed over the same time period and by the same approach so that assessments can be compared and aggregated. Our approach was adapted from methods used in the finance sector for risk management and insurance purposes. The parallel drawn here is as follows: regulators in the banking sector must ensure that banks have sufficient capital set aside in reserve, to cover unexpected losses and to prevent institutional failure. All bank assets – whether mortgages, loans, trading positions or other – are risk-weighted and aggregated to determine the amount to set aside against overall losses ([Hull, 2012](#); [Crouhy et al., 2014](#)). This standardized approach provided the inspiration for us to develop our P&D methodology.

The use of a standardized methodology for assessing the risk from individual assets by the finance sector allows rapid assessment in the timescales necessary for policy and business decisions to be made. It is separate from, but in addition to, the more detailed assessments made by bank employees when setting up financial transactions with customers. Similarly, the P&D methodology described here uses a standardized approach for rapid assessment of overall threats to woodland, but should be used in addition to the more detailed and nuanced assessments of individual P&D risks such as Pest Risk Assessments.

Methods

In this paper, [Hopkin's \(2014\)](#) definition of risk is used:

'the combination of the probability of an event and its consequence. Consequences range from positive to negative'.

Similarly, risk-weighted assets (RWA) (the assets of a financial institution weighted by risk and used to determine the amount of capital that must be set aside against potential losses) are determined by summing the risk of individual positions, each of which is calculated by multiplying the probability of a risk event occurring by an estimate of its financial consequence, expressed as a proportion of loss, which would be the worst-case loss. For example, credit risk (or the risk of default) for a mortgage position, would be calculated from the estimated likelihood of default of the counterparty multiplied by the worst-case loss that would occur if the mortgage defaulted. These risk values are then aggregated according to the level of assessment, e.g. departmental or bank level, and used to determine the amount of capital to set aside against losses ([Hull, 2012](#); [Crouhy et al., 2014](#)).

The detailed calculations for estimating probability and consequence for credit, market and operational financial risks are different. Our

approach to quantifying P&D risk is described here by comparison to the calculation of credit risk. RWA for Credit risk are calculated for each financial exposure of the bank (such as a mortgage or loan) and aggregated as per the following equation (1) ([Crouhy et al., 2014](#)):

$$RWA = \sum_i EAD_i \times LGD_i \times PD_i \quad (1)$$

where EAD, exposure at default (expressed in £); LGD, loss given default (expressed as a proportion); PD, probability of default (%); i, the *i*th financial exposure.

Our methodology adapts this calculation to the specific characteristics of P&D risk in order to address the identified gaps in P&D risk measurement. It is used to provide:

- Standardized risk-weighted assessments, defined as risk factors, of the threat from each individual P&D for each tree species in a woodland.
- Aggregated risk factors for each individual tree species from all P&D that threaten them.
- An aggregated risk factor of the overall risk to a woodland resource.

The P&D risk factors identify which P&Ds pose the biggest threats from the hundreds of known P&D threats. Risk factors at the tree species level provide a comparison of the relative threat to different tree species, and can assist in analyses of the risk vs return of planting different species. The final woodland resource risk factor provides an assessment of how much woodland is at risk.

It is important to note that risk-weighting P&D for risk management purposes is fundamentally different to forecasting the expected loss from each P&D. Risk factors for individual P&D are not expected to cover the potential loss from that individual P&D, in the same way that premiums for a single household insurance policy will not cover the cost of rebuilding that house if it burns down. However, the sum of all household premiums, are intended to cover the potential claims from all insured households ([Thoyts, 2010](#)). The sum of all risk factors for all P&D, taken together can help determine how much might be lost at the forest scale from all P&D. Risk factors at P&D level do however provide a means of comparing the relative risk from different P&D, in the same way that higher premiums relate to a higher assessment of insurance risk.

Risk assessment of this type uses a worst-case loss (also termed unexpected or catastrophic loss) for potential loss as opposed to the most likely or expected one. For wind risk to trees, for example, this would be the difference between average annual windthrow and the kind of devastation caused by a severe storm. Definitions of worst-case are set according to the confidence level sought but are close to 100 per cent. For example, in finance, the market risk assessment provides a value that should not be exceeded to a 99 per cent degree of confidence.

The adapted P&D methodology is presented below and then demonstrated by a case study of forest carbon projects certified under the UK WCC ([Forestry Commission, 2014](#)), and a sample of known P&D threats to British forests.

Calculation of individual P&D risk factors

The P&D risk factor calculation is adapted from equation (1). For credit risk, the 'probability of an event' as per Hopkin's definition, is the PD in equation (1). For P&D, this relates to the likelihood of arrival and establishment. Similarly, for credit risk, Hopkin's 'consequence' or impact is the LGD in equation (1). For P&D, this is the worst-case loss that could occur within the range of the P&D. The EAD in equation (1) is not required as we express the final risk factors as a proportion of tree species or woodland at risk rather than a financial value. P&D risk factors are estimated for each P&D/tree species combination for a given time period (*t*) and geographical area (*g*). The risk factor

(RiskFac) for a P&D: p_1 , affecting tree species: t_1 , is therefore estimated as follows:

$$\text{RiskFac}_{p1t1} = \text{ProbArr}_{p1} \times \text{ProbMax}_{p1} \times \text{ProbLoss}_{p1t1} \quad (2)$$

where ProbArr_{p1} , Annual probability of arrival and establishment of p_1 in geographical area (g) during time period (t) expressed as a per cent; ProbMax_{p1} , Maximum possible proportion of geographical area (g) that p_1 could impact; ProbLoss_{p1t1} , Worst-case loss from tree species t_1 , caused by p_1 within time period (t) within the potential range of p_1 expressed as a proportion.

Calculation of ProbArr

For endemic established pests this value is set to 100 per cent as the P&D is already established. Otherwise for P&D threats yet to arrive in geographical area (g) the percentage is estimated by the equation:

$$\frac{\text{total number of years in time period (t)}}{\text{estimated earliest year of arrival of PD in geographical area (g)}} \quad (3)$$

For example, if the period of assessment is 100 years and a P&D is estimated to arrive by year 20 then the annual probability of arrival (ProbArr) would be $100/20 = 5$ per cent.

Calculation of ProbMax

ProbMax is required as unlike financial transactions there is a geographic element to the worst-case loss from potential P&D, as the climate may not be suitable for the P&D within the area being assessed. ProbMax is an estimate of the proportion of the geographical area (g) that each P&D could inhabit if a suitable host tree species were present across the area, i.e. the full potential range of the P&D, expressed as a proportion of the geographical area (g) being assessed.

Calculation of ProbLoss

The potential worst-case loss during the time period (t) depends on:

- the year of arrival of the P&D;
- the fastest rate that the P&D could spread across the geographical area (g) being assessed, during the remaining period of assessment (i.e. assuming that the P&D arrives in the area (g) at the fastest possible point of dispersion);
- the age of trees that it affects; and
- the amount that can be recovered during the remaining time period by replanting.

The calculation of ProbLoss therefore requires a different approach to estimation for each practical application of this methodology, i.e. depending on the time period being assessed, age distribution of the tree species, definition of loss (e.g. yield reduction or mortality), and replanting options. However, the information on the fastest rate of spread of the P&D to its full range, the age of trees that it affects, and the worst-case impact on yield/mortality, is the same regardless of the application, and so this information need only be estimated once and can then be used in other applications of the method.

An estimate of the worst-case loss from each P&D/tree species combination needs to be estimated for each application. This is done by estimating the potential loss that could occur if the P&D arrived in each year during the time period (t), and then expanded at its fastest rate during the remaining time period, allowing for replanting, and taking into account the age distribution of the woodland resource being assessed. The worst-case loss is then the worst (highest) of these values. We demonstrate an example of this in the WCC case study, using possible years of arrival at 5-year intervals.

Calculation of individual tree species risk factors

In the credit risk example in equation (1), the risk-weighted assets for individual positions are summed to give the overall risk for an entity, e.g. department or bank as each exposure is mutually exclusive. However, the consequences or impacts of each P&D are not mutually exclusive as they affect the same woodland resource. More than one P&D could attack the same tree at the same time, however, P&D could also attack successively. For simplicity, we have assumed that P&D act successively and that P&D can only impact on the remaining trees after the previous P&D have attacked. For example, if P&D (p_1) has caused a loss of 5 per cent of a given tree species, and P&D (p_2) is estimated to cause a 10 per cent loss of trees, then p_2 can only affect the remaining 95 per cent of trees. Therefore, p_1 would cause a loss of 5 per cent of the tree species, leaving 95 per cent of the trees, and p_2 would cause a loss of 10 per cent of this remaining 95 per cent, i.e. 9.5 per cent. The total loss would therefore be 5 per cent + 9.5 per cent = 14.5 per cent.

Aggregation of the P&D risk factors for each tree species is therefore calculated by sequentially applying the risk factors for each individual P&D threat rather than summing them. The process of aggregating the P&D risk factors for a specific tree species is outlined in the sequential equations shown in (4). This example aggregates all the P&D risk factors that affect a given tree species (t_1). It includes risk factors $\text{RiskFac}_{p(1 \text{ to } n)t1}$, where n = the number of P&D affecting tree species t_1 . The variables $z_{(1 \text{ to } n)}$ are used to denote the interim values as each P&D risk factor has been aggregated, and which form an input to the next aggregation:

$$\text{RiskFac}_{p1t1} = z_1$$

$$\text{Aggregation of RiskFac}_{p2t1} = z_1 + (\text{RiskFac}_{p2t1} \times (100\% - z_1)) = z_2 \quad (4)$$

$$\text{Aggregation of RiskFac}_{p3t1} = z_2 + (\text{RiskFac}_{p3t1} \times (100\% - z_2)) = z_3$$

$$\text{Aggregation of RiskFac}_{p4t1} = z_3 + (\text{RiskFac}_{p4t1} \times (100\% - z_3)) = z_4$$

And so forth until:

$$\begin{aligned} \text{Aggregation of RiskFac}_{pnt1} &= z_{(n-1)} + (\text{RiskFac}_{pnt1} \times (100\% - z_{(n-1)})) \\ &= \text{Overall Risk Factor for tree species } t_1 = \text{RiskFac}_{t1} \end{aligned}$$

The risk factors for all of the P&D that affect each tree species being assessed are sequentially aggregated in this way to give a risk factor for each tree species.

Calculation of overall risk factor for the woodland resource

The final overall risk factor for the woodland resource being assessed is calculated by weighting the risk factors for each tree species by the proportion of that tree species across the woodland resource. So if there were three tree species (t_1 , t_2 and t_3) with risk factors of RiskFac_{t1} , RiskFac_{t2} and RiskFac_{t3} and concentrations (c) in the woodland of c_1 , c_2 and c_3 (expressed as a proportion of the total woodland occupied by the tree species), then the overall risk factor for the woodland resource (RiskFacWood) is calculated by:

$$\text{RiskFacWood} = (\text{RiskFac}_{t1} \times c_1) + (\text{RiskFac}_{t2} \times c_2) + (\text{RiskFac}_{t3} \times c_3) \quad (5)$$

Application of the P&D methodology to the WCC case study

Introduction to the WCC

The WCC, launched in 2011, is the UK standard for forest carbon projects (Forestry Commission, 2014). Under this standard, new woodland

projects are created to sequester carbon that can be sold as credits in the voluntary carbon market. The amount of carbon sequestered is measured periodically and verified by an independent third party. However, not all of the carbon is sold due to concerns over permanence. Permanence relates to the risk of reversibility caused by the premature release of carbon stored in forest biomass prior to project completion. A portion of the carbon from each project is set aside into a pooled buffer to provide compensation against future losses. The size of this buffer must be determined at the project outset. Under the current version of the Code (Forestry Commission, 2014), this entails a percentage potential loss assessment over the project duration for a specified list of risks, which includes P&Ds. The project developer carries out an assessment for each type of risk, which must fall within the specified range. The developer submits their methodology at verification (approval) by an independent assessor. Table 1 shows the risks and ranges for the current version of the Code, the current amount set aside for P&D ranging from 3 to 10 per cent:

General points of application

In this case study, we provide an overall assessment of risk to the projects certified under the WCC from a sample of P&Ds, to demonstrate the application of our approach, and how it might verify whether this range is likely to be adequate to cover future losses. The results will be used to demonstrate how the outputs can be used to support species selection, identification of priority P&D threats, and to support policy decisions such as whether the current buffer range is likely to be adequate against future losses.

The time period (*t*) was defined as 100 years – as this was the most common duration (53 per cent) of WCC projects at the time of assessment, as determined through an analysis of project documentation. The geographical area (*g*), was defined as Great Britain: the area over which the WCC projects are distributed. It was decided to perform the assessment for the main tree species in the portfolio, defined as those constituting more than 2 per cent of the total area of all projects, and for a sample of P&D. The analysis therefore required the following steps:

- Calculation of the concentration of different tree species within the WCC project area to provide the weights for the calculation of the overall risk factor for the woodland resource used in equation (5) and to identify those species to be assessed, constituting over 2 per cent of the project area;
- Identification of the P&D threats to these tree species;
- Choice of a sample of P&D to demonstrate the P&D methodology;
- Calculation of *ProbArr* and *ProbMax* in equation (2) for each P&D;
- Development of a simple spreadsheet to calculate *ProbLoss* in equation (2) for each P&D/tree species combination under the WCC scenario;
- Calculation of P&D, tree species and woodland resource risk factors.

Table 1 Buffer ranges for the WCC.

Risk categories	Buffer range %
Legal/social	1–2
Project management	1–3
Finance	2–5
Natural disturbance – Fire	2–4
Natural disturbance – Weather	3–6
Natural disturbance – Pest & Disease	3–10
Direct climate change effects	3–10

Calculation of the concentration of different tree species within the WCC

Each project under the WCC must create a Project Design Document (PDD) at the outset, which includes a breakdown of the species to be planted by hectare. PDDs were available for 60 of the 63 projects (which were either active or under validation as of January 2014). In total, these cover 2733 hectare. The PDDs were analysed to derive a list of all of the species representing over 2 per cent by area of the WCC projects.

For some small areas, PDDs did not provide species breakdowns but gave total hectares defined as, e.g. ‘mixed shrubs’, ‘mixed broadleaves’ along with a list of species. In these instances, the listed species were assumed to constitute an equal portion. Two of the project PDDs gave total hectares of ‘SAB’ (sycamore-ash-birch) woodland not broken down into constituent species and in these instances, the proportions were equally split between the three species. These breakdowns accounted for 3 per cent of the total 2733 hectare.

This method of selection takes no account of density of planting (i.e. number of trees per hectare). Forest Carbon Limited has been the main project developer to date under the WCC, and developed 47 of the 60 projects analysed. They provided a database of the total number of trees planted of each species for their projects (J. Hepburne-Scott, personal communication, 2014). This was used as a cross-check to verify if density of planting would identify significantly different proportions of tree species constituting over 2 per cent as opposed to using area.

Identification of the P&D threats to the main tree species

For each of the main tree species, a list of P&D to which they are susceptible was compiled. Existing well-established endemic P&D were identified through interviews with experts working for Forest Research (see Acknowledgements) and a literature review. P&D threats not yet present in Britain were identified using the UK Plant Health Risk Register (Defra, 2014b). A list of the P&D affecting a tree species can be extracted by entering the Latin name of a tree into the Register’s search function. Whilst this list may not be comprehensive it should contain the major known current threats. Once operational, the approach can be periodically updated with new P&D as they are identified.

Choice of a sample of P&D

A sample of 47 P&D (23 per cent of the 204 identified) was used to demonstrate the P&D risk methodology. The sample was chosen by first ranking the P&D according to the impact scores on the Plant Health Risk Register. The Register, however, evaluates the threat subjectively based on a range of impacts including impacts on the economy, human health and timber industry, whereas in this case study, we assess impact by mortality. This list was used to identify UK-based experts at Forest Research covering the top 30 P&D threats according to these impact scores. These experts were asked to highlight any additional P&Ds not identified in the top 30 using the Register scores that might lead to significant mortality. This included endemic pests at their full range, which are not included in the Register. Some P&D had to be excluded as expertise was not available, and some less threatening P&D were included to provide a broader demonstration of the approach. This led to a final sample size of 47.

Experts on each P&D then provided their best estimate of *ProbArr*, *ProbMax* and metrics required to calculate *ProbLoss*. Metrics estimated in this way are highlighted under the sections below as applicable.

Calculation of *ProbArr* and *ProbMax* in equation (2) for each identified P&D

As per equation (2), *ProbArr* is the ‘probability of arrival and establishment’ of each of the sample P&D in Great Britain in the next 100 years

expressed as a percentage. For endemic P&D *ProbArr* was set to 100 per cent as the P&D is already established.

For non-endemic P&D, *ProbArr* was estimated using values contained within The Plant Health Risk Register. The Register contains a metric for per cent likelihood of arrival and establishment that is a Likert scale from 1 to 5. Estimates of the year of arrival of each P&D were not available from the Register or Pest Risk Assessments and so conservative default values were used. Fewer than 25 major pests arrived in the UK between 1900 and 2010 (Defra, 2013), i.e. less than 1 every 4 years. It is not possible to quantitatively derive an estimate for individual P&D from this historic rate of arrival; however, it is clear that the historic rate of entry is low. An increase in shipping and other channels of arrival such as imported saplings suggest that this rate may increase in the future (Eschen et al., 2015). Default values were therefore set as 1–5 per cent, which conveniently corresponds to the 1–5 Likert Scale values from the Register. In the 100-year time horizon assumed for the WCC projects, this therefore implies an expected arrival of year 100 for the least likely (Likert Scale 1) and year 20 for the most likely (Likert Scale 5). All P&D are therefore assumed to arrive at some point within the time horizon of the project. Whilst subjective, these values are conservative and this was verified by the experts consulted. During the consultation, some of these Likert values were modified from their Register original values based on expert knowledge.

ProbMax is the maximum possible proportion of the geographic area (*g*) that each P&D could impact. For this case study, *g* is Great Britain and so experts were asked to estimate the maximum proportion of Britain by land area that the P&D range could expand to if a host tree species was present, e.g. the colder northern climate may limit some P&D that would not survive in this region.

Calculation of *ProbLoss* in equation (2) for each identified P&D/tree species combination

As per equation (2), *ProbLoss* is defined as the worst-case loss for a specific tree species/P&D combination that could occur in the next 100 years across Great Britain expressed as a proportion. For this specific case study, we created a spreadsheet-based Scenario Tool to estimate these values (available as Supplementary Data). We defined the worst-case loss as the worst-case loss of carbon that could occur in a 100-year project expressed as a proportion. Loss relates to mortality as if the host tree dies, the tree would be removed from the project and the sequestered carbon lost. A P&D that diminished the yield would result in less carbon being sequestered (and sold) than originally forecasted, but not a loss of verified sequestered carbon. When mortality occurs, it is assumed that the project will replant trees such that some of the lost carbon will be replaced by that sequestered in the new trees.

The Scenario Tool therefore estimates this worst-case loss for each P&D/tree species combination that could occur in 100 years, by calculating the potential loss that would occur if the P&D arrived in each 5-year interval up to 100 years, factoring in mortality rates, the age of trees affected, rate of spread, year of arrival of the P&D and time available for replanting and regrowth. The worst-case loss is then the highest of these potential losses.

In order to calculate this, the following metrics were estimated for each P&D through the expert consultation:

- *Age affected* – ‘Affected’ means causing mortality.
- *Current range in Britain* – proportion of Britain by area currently impacted by the P&D. Note this is not always the same as geographic spread. For example, the range for a soil fungus located in isolated foci throughout Britain would equate to the percentage of soil estimated to be infected.
- *Possible range in 100 years* – proportion of Britain that the P&D could cover in 100 years from its current range. For P&D not yet present, this is estimated assuming that the P&D arrives in year 1.

- *Years to full potential range* – the length of time the P&D is estimated to take to reach its full range. If the possible range in 100 years is less than the full range then this value is estimated assuming a linear rate of spread. For example, black stain root disease (*Grosmannia wagneriis*) is only expected to achieve a proportion of 0.10 of its range in 100 years.
- *Mortality by species* – the worst-case mortality caused by the P&D across its established range expressed as a proportion of trees lost. Where possible this should be estimated based on the worst known loss that has been caused by the P&D being assessed to date. Mortality rate has to relate to the defined range. In the black stain root disease example, the soil range infected is in isolated foci and the associated mortality proportion would relate to the mortality rate for trees on infected soil. So in a hypothetical area where infected soil was evenly scattered across a 100 km square covering a proportion of 0.10 of the area the range would be 0.10. Mortality could occur in a proportion of 0.9 of trees on infected soil only. However, for insects such as bark beetles, the range would be the geographic range of the beetle but not all trees within the area would be infected, so the range could be 100 km square but the mortality rate within that range would relate to the proportional mortality rate of tree species in the geographic range of the beetle. The combination of range and mortality should therefore represent the worst-case loss across Britain. It should be noted that P&D outbreaks often coincide with other natural events such as bark beetle outbreaks after a storm. The worst-case mortality would cover these possibilities as it is the worst possible case. Worst-case relates to the level of loss over the total British range so whilst losses may be high in locations with severe wind damage the mortality estimate will be lower at the national scale.

If a P&D is sublethal and does not cause mortality then *ProbLoss* is 0. For endemic species that are at their full range, *ProbLoss* is determined from the estimated mortality rate. For newly arrived P&D, the Scenario Tool is used to estimate *ProbLoss* for each P&D and tree species combination. For P&D already present, but not yet at their full range, the Scenario Tool estimates the loss for the spread to the remaining possible range only. *ProbLoss* is then the sum of the mortality rate weighted by the current range, and the loss factor weighted by the remaining range, i.e. the area that the P&D will spread to during the project duration.

The Scenario tool spreadsheet is based on a series of 20 tables. Each table assumes that the P&D arrives in a different year, and the tables represent different 5-year intervals from 0 to 95 years. In each table, an estimate of the loss that would occur by the end of the project if the P&D arrived at the beginning of that 5-year period is calculated. The worst-case loss is the highest loss from these 20 calculations. Range metrics are used to determine the rate of spread in 100 years and assumes a constant rate of spread. It is assumed that new trees would be planted to replace the lost trees in each of these years. The tool also factors in age susceptibility. For example, if trees are resistant to a particular P&D beyond age 20, then no losses would be calculated for the tables where the trees are beyond age 20 when the P&D arrives.

For the carbon loss estimation from mortality, the Tool uses estimated cumulative carbon sequestration values from look-up tables provided by the Forestry Commission (Forestry Commission, 2012) as specified in the associated WCC guidance (West and Matthews, 2012). These values are used to set base carbon levels at 5-year intervals up to 100 years. Some species do not have estimated sequestration value tables. For these, the default tables specified in the Guidelines are used. Of the species analysed, Scots pine (*Pinus sylvestris* L.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and oak (*Quercus* spp.) have specific carbon look up tables, whereas the remaining broadleaves use the SAB (Sycamore (*Acer pseudoplatanus* L.), Ash (*Fraxinus* spp.), Birch (*Betula* spp.) woodland) default table. Tables vary according to site productivity as measured by General Yield Class (GYC) (Matthews and Mackie, 2006).

Since GYC varies by project and the approach is providing an estimate for the whole WCC, the Guideline default recommendations of GYC4 were used, except for Sitka spruce where GYC6 was used (note that the GYC for Sitka spruce planted under the WCC is typically lower than that planted for timber alone). An initial plant density of 2500 trees per hectare and no thinning was assumed.

The Tool assumes that following loss, replacement trees are planted, and factors in replacement carbon sequestration. Since it is not known which species would be planted, the Tool uses the sequestration rates for generic SAB woodland as it is the only mixed woodland carbon sequestration estimate and is the default in the Guidelines for many species without individual tables.

In this way, the Tool estimates the losses that would occur by Year 100 for each 5-yearly arrival period. The worst-case loss *ProbLoss* is therefore the worst value (highest proportional loss) of these 20 values. This assessment is performed for each of the P&D and tree species combinations.

Calculation of P&D, tree species and woodland resource risk factors

Once the values required for *ProbArr*, *ProbMax* and *ProbLoss* were estimated in this way, individual P&D risk factors for each P&D/tree species combination were calculated using equation (2). They were then aggregated into tree species risk factors using the sequential application of equation (4) and then aggregated into an overall estimated risk factor for the woodland resource of the WCC using equation (5).

Results

The main tree species selected for the WCC case study

Table 2 shows the results of the analyses of tree species composition in the WCC projects from the two approaches: firstly the analysis of total hectares planted using PDDs, and secondly the cross-check using the number of trees planted on projects developed by Forest Carbon Limited.

The results show that these two approaches produced similar results in terms of identifying the main 11 tree species: using

the number of hectares planted instead of the number of trees is therefore not unduly biased. As a result, we used the hectare analysis from the PDDs to determine the sample of tree species for the case study as it covers all of the WCC projects (whereas Forest Carbon Limited projects only cover 47 of the 60 projects). All species constituting over 2 per cent were included in the sample. Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) is the only species not included, that would have been included if the Forest Carbon Limited data had been used instead as it constitutes over 2 per cent of the number of trees but not over 2 per cent of the number of hectares.

P&D threats to the main tree species

The analysis identified 204 P&D threats to the 11 tree species selected for assessment. Of these, 66 are already present in Britain, 137 are not present and the presence of bacterial blight of hazelnut (*Xanthomonas arboricola* pv. *corylina*) is unknown. The sample of 47 P&D therefore represented 23 per cent of this total.

Individual P&D risk factors

The key risk metrics and a demonstration of the calculation of individual P&D risk factors (equation 2) for a sample of assessed P&Ds is shown in Table 3.

The mulberry longhorn beetle (*Apriona germarii*) provides an example of where the final risk factor is adjusted to account for the fact that it would never cover all of Britain, i.e. multiplied by the maximum range of 0.5. Table 3 also shows how the risk factor varies significantly for P&Ds with similar metrics but where one is present and one is yet to arrive. *ProbLoss* is 0.89 for ash dieback (*H. pseudoalbidus*) and because the disease is already here the final risk factor is 89.3 per cent. However, whilst *ProbLoss* for the bronze birch borer (*Agilus anxius*) is also 0.89, because it has not yet arrived the final risk factor for this insect is 3.6 per cent.

Table 2 Breakdown of tree species for the WCC.

Species	% of total WCC from PDD (area analysis)	Cumulative % of ha	% of total WCC for FC projects (number of trees)
1. Birch (<i>Betula</i> spp.)	26.8	26.8	29.8
2. Oak (<i>Quercus</i> spp.)	15.8	42.7	10.4
3. Scots pine (<i>Pinus sylvestris</i> L.)	10.8	53.5	12.2
4. Ash (<i>Fraxinus excelsior</i> L.)	8.5	62.0	7.5
5. Sitka spruce (<i>Picea sitchensis</i> (Bong.) Carr.)	5.4	67.4	10.1
6. Rowan (<i>Sorbus aucuparia</i> L.)	4.2	71.5	6.0
7. Alder (<i>Alnus</i> spp.)	3.9	75.4	3.9
8. Sycamore (<i>Acer pseudoplatanus</i> L.)	3.4	78.8	2.8
9. Willow (<i>Salix</i> spp.)	3.1	81.9	4.6
10. Hazel (<i>Corylus avellana</i> L.)	2.4	84.3	1.7
11. Wild Cherry (<i>Prunus avium</i> L.)	2.0	86.2	1.1
12. Douglas-fir (<i>Pseudotsuga menziesii</i> (Mirb.) Franco)	1.4	87.7	2.2
13. Aspen (<i>Populus tremula</i> L.)	1.4	89.0	0.7
14. Hawthorn (<i>Crataegus</i> spp.)	1.1	90.1	1.0
15. Larch (<i>Larix</i> spp.)	1.0	91.1	1.2

Tree species risk factors

Table 4 demonstrates how the risk factors for each P&D that affect a given tree species are aggregated to determine the overall risk factor for that tree species, using birch and the P&Ds that affect it from the sample assessed. The P&D risk factors provide a comparison of the relative impact on carbon sequestration due to mortality for each P&D threat for birch.

Woodland resource risk factor

Table 5 presents the aggregation of the individual tree species risk factors into an overall assessment of the risk factor to the WCC projects (*RiskFacWood*). *RiskFacWood* is 12.1 per cent, i.e. the P&Ds assessed in the sample present a threat of loss of 12.1 per cent of the carbon in the WCC in a worst-case scenario.

Discussion

Since only a sample of P&D that threaten the tree species in the WCC were included in the case study, the initial results do not represent a final risk assessment for the WCC and it has not been possible to carry out any form of sensitivity analysis. However, the results do demonstrate how the approach works and the applicability of its findings. We are not aware of any other methods in the scientific literature that take such a holistic approach to assessing the future risk of P&D to woodlands.

Overall risk assessment at the woodland level

The woodland resource risk factor, *RiskFacWood*, provides an assessment of the worst-case loss to the woodland for the defined application. For the case study of certified projects under the WCC this value is 12.1 per cent. This represents an estimate of the potential worst-case loss of sequestered carbon sequestration from the P&D assessed in the sample.

RiskFacWood can be used to factor potential woodland loss into risk management decisions. Since this represents a worst-case loss as opposed to a forecast, the amount of loss factored into analyses can be varied according to the risk appetite of management. The more conservative the approach to risk, the greater the proportion of this risk factor used for analyses.

The case study of the WCC provides an example of this application. A key risk management decision application is whether the buffers set aside by forest projects to cover P&D risk are likely to be adequate. Table 1 shows that the current buffer range for assessments of P&D risk for the WCC is 3–10 per cent. If the buffer was inadequate and claims exceeded the carbon credits in it, the carbon market would be undermined, as credits that have been sold would have to be recalled to cover any shortfall in the buffer. The woodland risk factor of 12.1 per cent suggests that the buffer might not be adequate against future losses if the most conservative approach to risk (i.e. use of 100 per cent of this risk factor) is applied.

However, Table 5 also shows that 7.7 per cent of this total comes from the threat to ash which constitutes a proportion of 0.09 of the woodland and faces a significant mortality risk from both ash dieback (*H. pseudoalbidus/C. fraxinea*), which arrived in Britain in 2012, and the emerald ash borer (*Agrilus planipennis*),

which may arrive in future. Since projects are in their first few years, management could decide, for example, to replant alternative species now, exclude sales of sequestered carbon from ash in the short term, or reduce the amount of ash planted. Reducing the proportion of ash in favour of tree species with lower risk factors would reduce *RiskFacWood*.

In this way, the method provides a simple summary of the potential impact of P&D threats on the woodland resource and supports policy and management decisions to reduce this risk.

Tree species concentration risk

Table 5 also shows how the approach can identify concentration risk whereby a high degree of risk is concentrated in a few species. The analysis shows that the top 5 species (birch, oak, ash, Scots pine, Sitka spruce) account for a proportion of 0.67 of the WCC, which is therefore highly exposed to significant mortality to any of these species. Birch alone constitutes a proportion of 0.27 of the woodland certified under the Code and has the second highest risk factor.

The approach can be used to analyse why this is the case for the sample assessed, by comparing the P&D risk factors in the tree species risk factor calculations as demonstrated in Table 4. Comparison of the tree species risk factor calculations revealed that the risk factor for birch is higher than other broadleaves as, whilst they share key threats such as the citrus and longhorn beetles, birch faces an additional significant threat from the birch borer. It should be noted that this is a demonstration of the application as the comparison only relates to the P&D assessed. Once all P&D risk factors have been assessed and aggregated this relative risk is likely to change.

In terms of a demonstration of application: if the high risk to birch remains when all have been assessed this poses questions as to whether such reliance on birch as a pioneer species within the WCC should remain and whether there should be greater species diversification.

Identification and characteristics of the P&D presenting the highest risk

The approach helps identify which P&D are of most concern through a comparison of the risk factors for individual P&D. In addition, it identifies the characteristics of P&D that exhibit the highest potential threat for a specific application.

The WCC case study revealed that the later in the project cycle a P&D affects a woodland, the worse the carbon impact, as there is less time to replant and regrow lost carbon. The highest risk factors are for those P&D that affect mature trees and could spread rapidly across the country. The bronze birch borer (*A. anxius*) is yet to arrive in the country but has a high-risk factor of 3.6 per cent because it is estimated to take only 15 years to cover Britain, and could cause a proportional mortality rate as high as 0.9, partly caused by a judgement that birch in the UK may have a lower resistance than birch species in North America. The worst scenario is that it arrives in year 80 of a 100-year project and spreads across Britain by year 95, leaving only 5 years to replant and regrow carbon. Mature trees with high levels of carbon sequestration would be lost with minimal carbon replaced by any replanted saplings.

Table 3 Key risk metrics and sample P&D risk factor calculations (equation 2).

	Present in Britain?	Likelihood of arrival & establishment (%) <i>ProbArr</i>	Age affected	Current range in Britain (proportion)	Max potential range (proportion) <i>ProbMax</i>	Worst-case mortality in range (proportion)	Worst-case loss calculated in Scenario Tool (proportion) <i>ProbLoss</i>	% risk factor $ProbArr \times ProbMax \times ProbLoss$ <i>RiskFac_{P\&D/tree}</i>
Ash dieback (<i>Hymenoscyphus pseudoalbidus</i> , <i>Chalara fraxinea</i>)	Y	100	All	0.1	1.0	Ash: 0.95	Ash: 0.89	Ash: 89.3
Asian longhorn beetle ¹ (<i>Anoplophora glabripennis</i>)	N	5	>20 years	0	1.0	Broadleaves: 1.00	Broadleaves: 0.58 ²	Broadleaves: 3.0
Black stain root disease (<i>Grosmannia wagneri</i>)	N	3	10–20 years	0	1.0	Scots pine: 0.50	Scots pine: 0.00	Scots pine: 0
Bronze Birch Borer (<i>Agrilus anxius</i>)	N	4	>5 years	0	1.0	Birch: 0.90	Birch: 0.89	Birch: 3.6
Citrus longhorn beetle ³ (<i>Anoplophora chinensis</i>)	N	4	>20 years	0	1.0	Broadleaves: 1.00	Broadleaves: 0.58	Broadleaves: 2.3
Emerald ash borer (<i>Agrilus planipennis</i>)	N	5	All	0	1.0	Ash: 0.80	Ash: 0.78	Ash: 3.9
Large brown pine weevil (<i>Hylobius abietis</i>)	Y	100	<8 years	1.0	1.0	Sitka: 0.25 Scots pine: 0.25	Sitka: 0.00 Scots pine: 0.00	Sitka: 0.4 Scots pine: 0.0
Mulberry longhorn beetle (<i>Apriona germarii</i>)	N	3	All	0	0.5	Willow: 0.01	Willow: 0.01	Willow: 0.0

¹From the case study: Sycamore, Alder, Birch, Hazel and Willow but not Ash, Wild Cherry, Oak or Rowan.²Calculation of this ProbLoss for broadleaves/Asian longhorn beetle is provided as an example in the Scenario Tool in the Supplementary Material.³From the case study: Sycamore, Alder, Birch, Hazel, Willow, Ash, Wild Cherry, Rowan but not Oak.

Table 4 Aggregation of P&D risk factors to a tree species risk factor: *Betula* (equation 4).

Birch (<i>Betula</i>)	% risk factor	Cumulative risk factor equation (4) (%)
Bronze Birch Borer (<i>A. anxius</i>)	3.6	3.6
<i>Anisogramma virgultorum</i>	0.3	3.9
Citrus longhorn beetle (<i>A. chinensis</i>)	2.3	6.1
Asian Longhorn Beetle (<i>A. glabripennis</i>)	2.9	8.9
Honey Fungus, Root Rot (<i>Armillaria mellea</i>)	0.3	9.1
<i>Discula betulina</i>	0.0	9.1
<i>Melampsorium betulinum</i>	0.3	9.4
Oak Pinhole Borer (<i>Platypus cylindrus</i>)	0.0	9.4
..... Additional P&D not yet assessed...		
Tree species risk factor (for sample of P&D assessed to date). RiskFac _{Betula} :		9.4

Table 5 Aggregation of tree species risk factors for the WCC based on a sample of 23% of identified P&Ds (equation 5).

Tree species	Risk factors ($RiskFac_{tree}$) (%)	WCC species breakdown (proportion)	Weighted risk factors (%)
Sycamore (<i>A. pseudoplatanus</i>)	5.4	0.03	0.2
Alder (<i>Alnus</i>)	5.4	0.04	0.2
Birch (<i>Betula</i>)	9.4	0.27	2.5
Hazel (<i>Corylus</i>)	5.4	0.02	0.1
Ash (<i>Fraxinus</i>)	90.1	0.09	7.7
Sitka spruce (<i>P. sitchensis</i>)	6.4	0.05	0.3
Scots pine (<i>P. sylvestris</i>)	2.5	0.11	0.3
Wild cherry (<i>P. avium</i>)	3.2	0.02	0.1
Oak (<i>Quercus</i>)	2.5	0.16	0.4
Willow (<i>Salix</i>)	5.4	0.03	0.2
Rowan (<i>Sorbus</i>)	3.2	0.04	0.1
Total:		0.87	12.1 ($RiskFac_{Wood}$)

By contrast, the lowest risk factors are for P&D that only kill young trees, as only small amounts of carbon are lost and there is time to replant and regrow given the long timescale. The large brown pine weevil (*Hyllobius abietis*), for example, is well established throughout Britain but despite a potential proportional mortality rate of 0.25 it only affects trees up to age 8, so has a risk factor of only 0.40 per cent.

The P&D risk factors therefore help direct attention to which P&D pose the highest risk to forest carbon projects and warrant further research and management action. From the sample, these include the Asian longhorn beetle (*Anoplophora glabripennis*) and citrus longhorn beetle (*Anoplophora chinensis*); as well as

the bronze birch borer with risk factors of 2.91, 2.33 and 3.57 per cent, respectively. The risk factors for the longhorn beetles are less than that for the borer as they are expected to take around 60 years to cover Britain rather than 15 years for the borer.

Different risk assessments needed for different applications

The case study demonstrates that the determination of the worst-case impact from P&D varies according to whether it is assessed for timber, carbon or other applications. For carbon, the worst-case relates to mortality. The calculation of *ProbLoss* for other applications will vary as the following examples illustrate:

- The oak processionary moth (*Thaumetopoea processionea*) has a high impact score in the Risk Register: as caterpillar hairs can cause severe irritation to humans; however, this has little implication for timber or carbon purposes.
- Ash dieback (*H. pseudoalbidus/C. fraxinea*) may have less of an impact on the timber sector than on carbon projects. Mortality could be slow and the wood can still be used in some markets for timber. Slow mortality does not assist carbon projects as later loss of more mature trees reduces the time for replanting and if trees are removed from carbon projects then all of the associated carbon credits must be cancelled under current policy.
- Timescales differ. Timber rotations are generally of shorter duration than carbon projects, and so *ProbLoss* will need to be estimated based on a shorter timescale than the case study.
- Some P&D damage timber quality rather than inducing mortality. The oak pinhole borer (*Platypus cylindrus*) is such an example. It stains timber and can therefore impact on timber revenues but does not cause high mortality so it has little impact on carbon projects.
- Similarly, some P&D only affect visual appearance, such as the horse chestnut scale (*Pulvinaria regalis*). It causes foliar spots. Others may only affect the fruit, which impacts on amenity and commercial value but not on carbon.

The *ProbLoss* calculation therefore needs to be adapted according to application and how loss is defined.

Identification of unique risk characteristics

The approach can reveal hitherto unrecognized risks or indeed factors that reduce risk. The case study revealed that for tree species that demonstrate the slower rates of carbon sequestration, early attack from a P&D could result in an overall net gain of carbon by the end of the project if a faster growing replacement species is planted. This partially accounts for the relatively low-risk factor for Scots pine compared with other species in the example, as it had the slowest carbon sequestration rate of the species covered. For example, black stain root disease of conifers (*G. wageneri*), causes proportional mortality of around 0.5 in infected Scots pine trees of 10–20 years in age. As the methodology assumes replacement planting with mixed broadleaved woodland, the results showed a positive P&D Risk Factor over the project. In these instances, the P&D Risk Factor was set to 0 per cent.

'Rapid' consolidation of myriad risks into single measures for management and policy

The approach does not replace the need for detailed individual pest risk assessments, or detailed loss estimates for significant P&D threats; however, such tailored individual modelling cannot realistically be consolidated and regularly updated for over 200 individual P&D risks within the timeframes required for management and policy decisions. The use of a standard calculation based on a small range of key metrics has the potential to support more rapid consolidated risk assessment for individual tree species and woodland resources. It also helps isolate which P&D are likely to be the highest threats and warrant focused research.

Information requirements and future research needs

Pest Risk Assessments are the primary existing tool for assessing the risk from new and existing individual P&D but the case study revealed that they lack standardized quantified information on key metrics such as per cent likelihoods of arrival and establishment; mortality rates; and rates of spread. It is highly recommended that these metrics are added to future Pest Risk Assessments. Inclusion of these metrics is critical to developing more accurate quantified risk assessments demanded by a range of forest stakeholders. The list of metrics identified here would represent a minimum, however, likely range under future climate scenarios within the country being assessed would also enhance the ability to develop quantified risk assessments under future climates. Yield reduction figures that would be required for an analysis of risk to timber projects are also rarely included.

Accurate estimates of growth and sequestration rates for carbon and timber purposes are also required for quantified risk assessments in the countries being assessed. The case study demonstrated that more tables are required for risk assessments in Britain as many key species are not covered in the existing information. This is particularly true as the mixed broadleaved woodland (sycamore-ash-birch) table has limitations as a default estimate, as it shows continuing sequestration up to 200 years of age, however many of the species which use this as a default – including birch, rowan (*Sorbus aucuparia* L.), alder (*Alnus* spp.), willow (*Salix* spp.), hazel (*Corylus avellana* L.) and wild cherry (*Prunus avium* L.) – do not typically live for 100 years.

Sequential P&D attack vs combined attack

The methodology assumes that P&D attack the woodland resource sequentially, i.e. a second P&D attacks the remaining trees that are left after mortality caused by the first P&D is complete. In reality, a second P&D attack may occur at the same time as the first, which could result in a different mortality outcome. Depending on the P&D combination this could be higher or lower than the impact of sequential attack. This is not factored into the current methodology.

Conclusion

The P&D methodology presented here represents a significant step forwards in the risk assessment of future P&D threats. It does not rely on historical trends to predict future losses, but

proposes the systematic quantification of all future threats from known P&D and their aggregation to derive assessments of the threats to individual trees species and to woodland resources.

As the case study demonstrates, P&D risk factors for individual P&Ds allow identification of those, which pose the greatest threat and warrant increased attention. The approach helps eliminate those P&D that cause minimal loss, only affect young trees, are very slow spreading, or are only ever likely to cover a small range. The approach could therefore be used to narrow down the somewhat overwhelming lists of hundreds of potentially threatening P&D into those that pose a significant threat. This could help prioritization of scarce resources for more detailed pest risk assessments, or preventative action.

Tree species risk factors can support management decisions on species selection, as they can be factored into risk vs reward analyses, for example, whether to plant Sitka spruce (*P. sitchensis*) or Scots pine (*P. sylvestris*). The key issue is whether any higher rewards, such as the higher yield from Sitka, offset any higher risks. The approach could be used to compare whether the risk to Sitka from P&D is higher than that for Scots pine, and if so whether the rate of growth is sufficient to offset this higher risk. The P&D risk factors could also be fed into existing models comparing tree species for planting (Meason and Mason, 2014).

Weighting tree species by their concentration to provide a risk factor for the woodland shows the impact that the loss of a given species might have. This could provide justification for policy decisions on whether to increase expenditure on preventative measures against P&D identified as a high threat. Overall woodland risk assessments can also be factored into broader management and policy-related decisions on the need to protect woodland resources.

Risk assessments have to be made to support management decisions in a timely manner regardless of the state of information. The approach provides a framework for the risk calculations and utilizes the best available data for the metrics, which can be refined as better data becomes available. As an interactive tool, users can change parameters to see how actions might impact on risk, and to see how sensitive the results are to metrics for which the data is less certain.

Risk assessments are never 100 per cent accurate as risk can never be forecast with certainty. The methodology is primarily a tool to help understand risk and take action. Risk measurement is not risk management. Measurement is passive; but without action there is no risk management and the threats remain. The approach represents a powerful tool to evaluate potential risks and direct action where it is most needed.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

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